Bottom Spectroscopy at CDF

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Outline

- Motivation
- Review on heavy hadrons spectroscopy during CDF Run II
- Latest results
  - Evidence of $Y(4140)$
  - Observation of $\Xi_c^-$ and $\Omega_c^-$
  - Polarization of $\Upsilon(1S)$
- Conclusion
Delivered luminosity: $\sim 8 \text{ fb}^{-1}$

Acquired luminosity: $\sim 7 \text{ fb}^{-1}$

CDF has excellent vertex and momentum resolution

This talk: analysis covering up to 4.2 $\text{ fb}^{-1}$
Heavy Spectroscopy it is important:

- The study of heavy spectroscopy increases our knowledge on QCD.
- Study of B hadrons = study of (non-perturbative) QCD
- Heavy quark hadrons are the hydrogen atom of QCD

B hadrons = hydrogen atom of QCD
Tevatron is a suitable place to study bottom spectroscopy

- All $B$ hadrons are copiously produced.
  - Some states are not accessible to B factories.

- They are produced boosted
  - separation between produced and decay $B$ hadron vertex is measurable.
  - low $p_T$ daughters are tracked.

- CDF has a strong program on heavy hadron spectroscopy that yielded many key results.
Heavy $B$ Hadrons

Until 2006 $\Lambda^0_b = |bdu\rangle$ was only established $B$ baryon

$\Rightarrow$ Search for

$\Sigma^-_b = |bdd\rangle$

$\Xi^-_b = |bds\rangle$, $\Omega^-_b = |bss\rangle$

Total spin: $1/2$ ($X_b$) or $3/2$ ($X^*_b$):

$b\{qq\}$, $q = u, d, s$; $J^P = S_Q + s_{qq}$

- $\Sigma^\pm_b$ and $\Sigma^{*\pm}_b$ discovered in 2007
- $\Xi^-_b$ discovered in 2007
- $\Omega^-_b$ discovered in 2008
Review on CDF Charm and Bottom Results
Observed by CDF in 2007:
\[ \Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi^{\pm} \]
\[ (\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-, \Lambda_c^+ \rightarrow PK^- \pi^+) \]
Signals with \( > 5\sigma \) significance

<table>
<thead>
<tr>
<th>State ( \Sigma_b )</th>
<th>Yield</th>
<th>( Q ) or ( \Delta \Sigma_b^{*} ) (MeV/c(^2))</th>
<th>Mass (MeV/c(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma_b^+ )</td>
<td>( 32^{+12+5}_{-12-3} )</td>
<td>( Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3} )</td>
<td>( 5807.8^{+2.0}_{-2.2} \pm 1.7 )</td>
</tr>
<tr>
<td>( \Sigma_b^- )</td>
<td>( 59^{+15+9}_{-14-4} )</td>
<td>( Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2 )</td>
<td>( 5815.2 \pm 1.0 \pm 1.7 )</td>
</tr>
<tr>
<td>( \Sigma_b^{*+} )</td>
<td>( 77^{+17+10}_{-16-6} )</td>
<td>( \Delta \Sigma_b^{*} = 21.2^{+2.0+0.4}_{-1.9-0.3} )</td>
<td>( 5829.0^{+1.6+1.7}_{-1.8-1.8} )</td>
</tr>
<tr>
<td>( \Sigma_b^{*-} )</td>
<td>( 69^{+18+16}_{-17-5} )</td>
<td>( \Delta \Sigma_b^{*-} = 21.2^{+2.0+0.4}_{-1.9-0.3} )</td>
<td>( 5836.4 \pm 2.0^{+1.8}_{-1.7} )</td>
</tr>
</tbody>
</table>
$B_c^{\pm} \rightarrow J/\Psi \pi^{\pm}$

$m = 6275.6 \pm 2.9 \ (stat) \pm 2.5 \ (syst) \ \text{MeV}/c^2$


Theoretical expectations:

- non-relativistic potential models: $6247 - 6286 \ \text{MeV}/c^2$
- lattice QCD: $6304 \pm 12^{+18}_{-0} \ \text{MeV}/c^2$
$X(3872) \rightarrow J/\psi \pi^+ \pi^-$

- $m(X(3872)) = 3871.61 \pm 0.16(\text{stat}) \pm 0.19(\text{syst})$ MeV/c$^2$
  (more precise measurement)
- Angular analysis $\rightarrow J^{PC} = 1^{++}$ or $2^{--}$ only assumptions compatible with data

(CDF Run II
L $\approx$ 780 pb$^{-1}$
- data points
acc. corrected prediction for

\[ B^{**}_s \to B^+ K^- \]

\[ B^{**}_s \to B^+ K^- \] and
\[ B^{**}_s \to B^{**} K^- (B^{**} \to B^+ \gamma, \text{ with } \gamma \text{ missing}) \]

Two \( B^+ \) Decay channels explored:

- \( B^+ \to J/\psi K^+ (J/\psi \to \mu^+ \mu^-) \)
- \( B^+ \to D^0 \pi^+ (D^0 \to K^- \pi^+) \)


- \( m(B_{s1}) = 5829.41 \pm 0.21 \text{(stat)} \pm 0.14 \text{(syst)} \pm 0.6 \text{(PDG)} \text{ MeV}/c^2 \)
- \( m(B^{*}_{s2}) = 5839.64 \pm 0.39 \text{(stat)} \pm 0.14 \text{(syst)} \pm 0.5 \text{(PDG)} \text{ MeV}/c^2 \)

(first observation of \( B_{s1} \))
Evidence for $Y(4140) \rightarrow J/\psi \Phi$

- Since the discovery of $X(3872)$ more exotic mesons with charmonium-like decay modes have been observed.

- The possible interpretations beyond standard quark model such as hybrid ($q\bar{q}g$) and four-quark states ($q\bar{q}q\bar{q}$) motivates the interest in exotic mesons in the charm sector.

- The observation of $Y(3930)$ near the $J/\psi \Omega^-$ threshold motivates searches for similar phenomena near the $J/\psi \phi$ threshold.
Evidence for $Y(4140) \rightarrow J/\psi \Phi$

$B^+ \rightarrow Y(4140)K^+$; $Y(4140) \rightarrow J/\psi \Phi$
($J/\psi \rightarrow \mu^+\mu^-; \Phi \rightarrow K^+K^-$)

- $m = 4143.0 \pm 2.9$ (stat) $\pm 1.2$ (syst) MeV/c$^2$
- $\Gamma = 11.7^{+8.3}_{-5.0}$ (stat) $\pm 3.7$ (syst) MeV/c$^2$
- statistical significance 3.8 $\sigma$

\[ \Xi_b^− \rightarrow J/\psi \Xi^− \]
\[ (J/\psi \rightarrow \mu^+ \mu^−, \Xi^− \rightarrow \Lambda \pi^−) \]

\[ \Omega_b^− \rightarrow J/\psi \Omega^− \]
\[ (J/\psi \rightarrow \mu^+ \mu^−, \Omega^− \rightarrow \Lambda K^−) \]

\[ \Xi^− \text{ and } \Omega^− \text{ long lived & charged} \]
\[ (cτ(\Xi^−) \approx 5 \text{ cm}, cτ(\Omega^−) \approx 2.5 \text{ cm}) \]
- They are tracked in the silicon vertex detector
- This improve significantly the purity of the samples.

Likelihood method to extract mass, yield and significance:
\[ \mathcal{L} = \prod_i^N (f_s G(m_i, m_0, s_m \sigma_i^m) + (1 - f_s) P^n(m_i)) \]
M(Ξ⁻) = 5790.9 ± 2.6(stat) ± 0.8(syst) MeV/c²
(Phys.Rev.D80,072003,2009)

Consistent with theory:
5790 – 5814 MeV/c²

lifetime measurement:
τ(Ξ⁻) = 1.56^{+0.27}_{-0.25} ± 0.02 ps
(first exclusive Ξ⁻ lifetime)
CDF observed $\Omega_b^-$ in 2009 (Phys.Rev.D80,072003,2009)

- $m(\Omega_b^-) = 6054.4 \pm 6.8 \text{(stat)} \pm 0.9 \text{(syst)}$ MeV/c$^2$
- $\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40} \pm 0.8$ ps (first time)

Consistent with theory:

- theory expect: $6010 - 6070$ MeV/c$^2$
\( \Omega_b^- \) Discrepancy DØ - CDF

\( \Omega_b^- \) first observation by DØ: \( 6165 \pm 10 \) (stat) \( \pm 13 \) (syst) MeV/c²


6σ disagreement with CDF!

\[ \Delta m = (111 \pm 12 \pm 14) \text{ MeV/c}^2 \]

Discrepancy also in \( \Omega_b^- \) production rate:

- DØ: \[ \frac{f(b \rightarrow \Omega_b^-) B(\Omega_b^- \rightarrow J/\psi \Omega^-)}{f(b \rightarrow \Xi_b^-) B(\Xi_b^- \rightarrow J/\psi \Xi^-)} = 0.80 \pm 0.32^{+0.14}_{-0.22} \]

- CDF: \[ \frac{\sigma B(\Omega_b^- \rightarrow J/\psi \Omega^-)}{\sigma B(\Xi_b^- \rightarrow J/\psi \Xi^-)} = 0.27 \pm 0.12 \pm 0.01 \]

→ DØ working on an update of \( \Omega_b^- \) with more data

Measured and Predicted Masses for the \( \Xi_b^- \) and \( \Omega_b^- \)

- Jenkins (PRD 77,034012(2008))
- Lewis et al, (PRD 79,014502(2009))
- Systematic Uncertainties
Vector meson production and polarization is discussed within the framework of non-relativistic QCD.

Theory predicts the vector meson polarization become transverse in the perturbative regime (at large $p_T$).

Recent CDF measurements of polarization for $J/\psi$ and $\psi(2S)$ do not support this prediction.

It is helpfull for our understanding test if $\Upsilon(1S)$ also is in disagreement with the theoretical predictions.
\( \Upsilon(1S) \) Polarization

- \( \Upsilon(1S) \rightarrow \mu^+ \mu^- \)
- \( |y| < 0.6 \)
- \( 2 < p_T(\Upsilon(1S)) < 40 \text{ GeV/c} \)

→ NRQCD expect transversal polarization at high \( p_T \)
→ CDF observe longitudinal polarization at high \( p_T \)

\( \theta^* \) is the angle between \( \mu^+ \) and \( \Upsilon(1S) \) lab direction in \( \Upsilon(1S) \) rest frame.
Conclusions
Conclusions

- Very rich heavy flavour program at CDF

- Many results on properties of heavy B hadrons:
  - Heavy baryons $\Sigma^\pm_b$, $\Sigma^{*\pm}_b$, $\Xi_b^-$ established
  - $\Omega^-_b$ observation
  - $\Upsilon(1S)$ polarization

- CDF will keep as a reference in the study of heavy hadrons next years
  - CDF accumulates more data until end of Run II
CDF:

\[
\frac{\sigma(\Xi_b^-)B(\Xi_b^- \to J/\psi \Xi^-)}{\sigma(\Lambda_b^0)B(\Lambda_b^0 \to J/\psi \Lambda)} = 0.167^{+0.037}_{-0.025} \pm 0.012
\]

\[
\frac{\sigma(\Omega_b^-)B(\Omega_b^- \to J/\psi \Omega^-)}{\sigma(\Lambda_b^0)B(\Lambda_b^0 \to J/\psi \Lambda)} = 0.045^{+0.017}_{-0.012} \pm 0.004
\]

DØ:

\[
\frac{\sigma(\Xi_b^-)B(\Xi_b^- \to J/\psi \Xi^-)}{\sigma(\Lambda_b^0)B(\Lambda_b^0 \to J/\psi \Lambda)} = 0.28 \pm 0.09(stat)^{+0.09}_{-0.08}(syst)
\]

CDF, DØ results and theoretical prediction are consistent.
Excellent momentum resolution

particle ID (TOF & dE/dx)

Displaced track trigger and di-muon triggers